RI 9040

Bureau of Mines Report of Investigations/1986

Direct Measurement of Longwall Strata Behavior: A Case Study

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UNITED STATES DEPARTMENT OF THE INTERIOR

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Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Listak, Jeffrey M
Direct measurement of longwall strata behavior.

(Bureau of Mines report of investigations; 9040)

Bibliography: p. 19.

Supt. of Docs. no.: I 28.23: 9040.

1. Longwall mining. 2. Rock deformation. I. Hill, John L. II. Zelanko, Joseph C. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines); 9040.

TN23.U43 [TN275] 622 s [622'.28] 86-600097

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	psi	pound per square inch
in	inch	$\mu s/ft$	microsecond per foot
lb	pound	st	short ton
pct	percent		

DIRECT MEASUREMENT OF LONGWALL STRATA BEHAVIOR: A CASE STUDY

By Jeffrey M. Listak,[1] John L. Hill III,[1] and Joseph C. Zelanko[1]

ABSTRACT

The Bureau of Mines has conducted a rock mechanics study to monitor deformation of near-seam strata above a longwall panel in the Pittsburgh Coalbed. The primary goal was to determine the height of caving immediately behind advancing longwall face supports. This study, although site specific, provides information on the caving mechanism associated with longwall extractions so that strata behavior and its interaction with longwall face supports can be better understood.

Two holes were drilled, approximately 550 ft apart along the centerline of a longwall panel, from the surface to the coalbed approximately 650 ft below. Various downhole geotechnical instruments were used to monitor strata deformation. In addition, surface elevation surveys were conducted to differentiate between surface and subsurface activity.

This report discusses the caving characteristics of the strata as the longwall panel approached and passed beneath the boreholes. Physical property data are also presented to demonstrate the relationship between caving behavior and local geology. Data show that immediate caving of strata above the longwall face occurred at a height less than 23.5 ft and that strata behavior above longwall extractions is highly dependent upon lithology, with major disturbances occurring at weak lithologic zones.

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INTRODUCTION

Several analytical methods have been developed to predict longwall strata behavior and associated face support loading. However, very few systematic studies that actually monitored the caving mechanism associated with longwall mining have been conducted. To develop a better understanding of longwall strata behavior and its interaction with longwall face supports, the Bureau of Mines installed various geotechnical instruments in two boreholes drilled over a longwall extraction located in southwestern Pennsylvania. This study is intended to lay the groundwork for additional research in order to develop a data base for strata behavior above longwall extractions. The information from these studies could effectively improve the method for selecting longwall roof support capacities.

Some methods (1-3)[2] for selecting the proper load capacity of longwall roof supports are based on the assumption that some finite volume of roof material, often assumed to be cubic or parallelepiped in geometry, is being held up by the support. The boundaries of this volume of material are defined by the spacing of the supports (width), the supporting distance from face to gob (length), and the height and angle of caving. While the support spacing and distance from face to gob are measurable dimensions, the height of caving must generally be estimated. Caving height is usually estimated as a constant times the height of extraction, the constant being determined by estimating the bulking factor of caved material.

Formulas using assumed caving heights for predicting load density vary considerably. For example, Wilson (1) assumes that caved rock occupies 1.5 times the volume of the same rock in situ; therefore, the height of caving (above the level of the roof) is twice the extraction height. Wade (2), however, assumes that caved material will occupy 1.25 times the volume of rock in situ, yielding a caving height equal to four times the extraction height.

To find the caving horizons above a longwall panel extraction, two instrumentation stations were installed in vertical boreholes located along the centerline of one longwall panel. Each station utilized instruments that measured both horizontal and vertical displacements as a function of time and longwall face advance. In addition, surface elevation surveys were performed to differentiate between surface and subsurface displacements.

ACKNOWLEDGMENTS

The authors thank Roctest, Inc.,[3] Plattsburgh, NY, for cooperation in designing, manufacturing, and installing the borehole instrumentation. Special thanks goes to Girard Theroue and David Prentice of Roctest, Inc., for their assistance at the field site.

[2] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

[3] Reference to specific manufacturers does not imply endorsement by the Bureau of Mines.

DESCRIPTION OF TEST SITE

The longwall panel under investigation is located within the Appalachian Plateau Province of southwestern Pennsylvania. Structural relief in the region does not exceed 350 ft, and dips are generally less than 4°. Mining takes place in the Pittsburgh Coalbed, which lies stratigraphically within the Pennsylvania Age coal-bearing strata of the Monongahela Group (fig. 1). Figure 2 illustrates the lateral continuity of this interval over the panel under study. The panel (panel 3) is 630 ft wide and 5,570 ft long. A four-entry headgate and tailgate system is used with square pillars on 95-ft centers and entries 15 to 18 ft wide. Mining height is 5.8 ft.

Roof support along the face was maintained by 460-st two-leg shield supports with setting pressures of 3,600 psi. The rate of advance for the longwall face was approximately 35 ft per three-production-shift day.

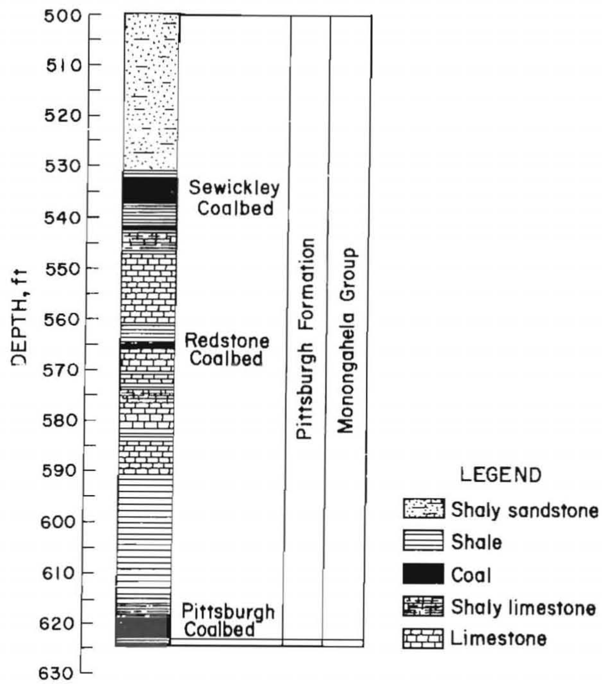

FIGURE 1.—Generalized stratigraphic column of the Monongahela Group.

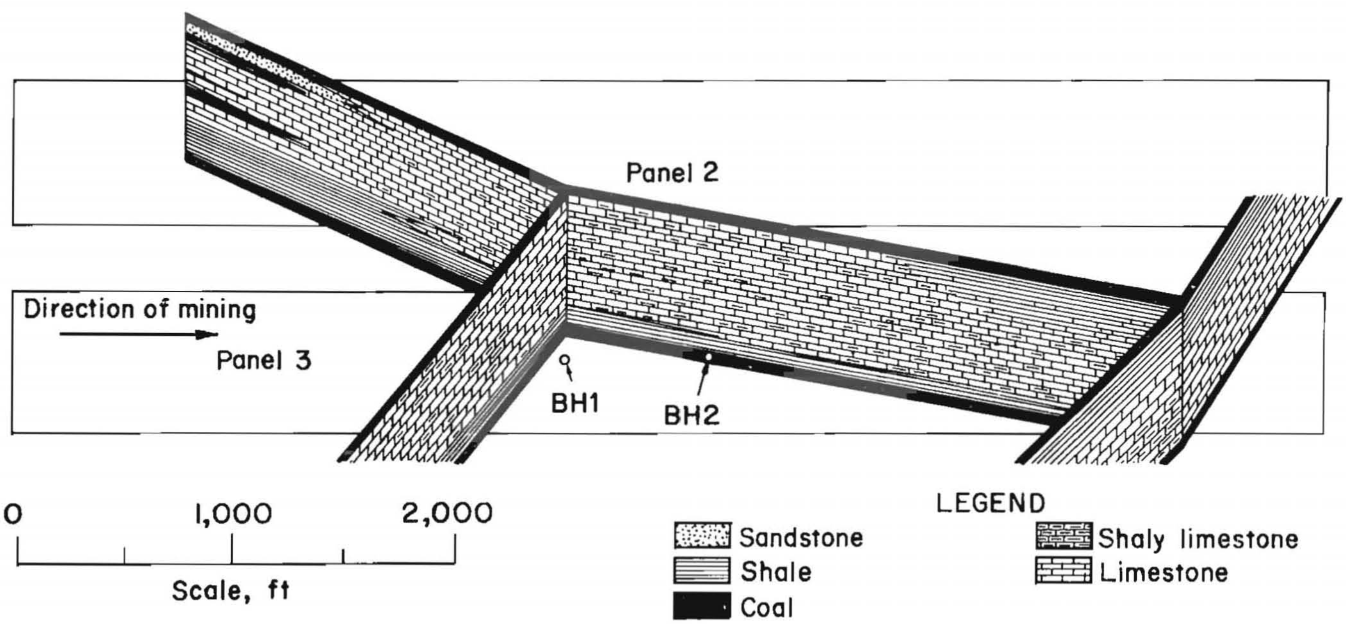

FIGURE 2.—Fence diagram of strata overlying the study panel.

SITE PREPARATION--BOREHOLE DRILLING

Several factors were considered during site selection, including topography and terrain, surface rights (private land ownership), and environmental restrictions. However, the most important technical consideration was to choose the test site that would yield representative results over the length of the panel. Therefore, in addition to the nontechnical considerations, borehole locations were chosen toward the center and along the length of the centerline of the panel to minimize the effects of the panel boundaries on the caving process. The two borehole monitoring stations were located at distances of 2,600 and 3,150 ft from the start of the panel (fig. 3).

Two 6-in-diam boreholes were drilled through the coalbed. With the exception of a 15-ft standpipe at the surface, the holes were not cased. This allowed the borehole anchors to be set directly in distinct stratigraphic members. A combination of rotary and core drilling was used to drill the first borehole (BH1). One hundred feet of core was extracted from BH1 for descriptive geologic logging and laboratory testing. This interval included the entire interburden between the Sewickley and Pittsburgh Coalbeds. The surface at BH1 had a mean sea level elevation of 1,004.68 ft with a borehole depth of 630 ft. This final depth was approximately 3 ft below the base of the Pittsburgh Coalbed. Geophysical logging was performed on each hole to determine lithology and the location of water-bearing strata. These logs were also used to calculate a rock strength index.

The quality of the borehole is of utmost importance. It must be straight and free of obstructions so that problems during instrument installation can be minimized. However, in this study borehole conditions were not ideal. This prevented placement of borehole anchors at desired depths (5 ft above the coalbed), so caving immediately behind the longwall supports could not be detected. Figure 4 shows a borehole directional survey of station BH1. Although the horizontal difference between the top and

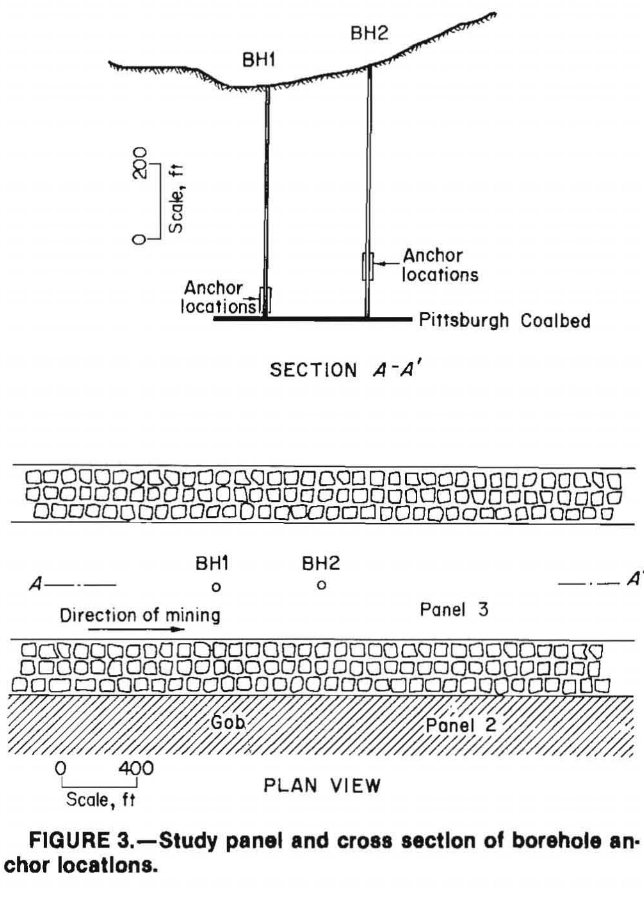

FIGURE 3.—Study panel and cross section of borehole anchor locations.

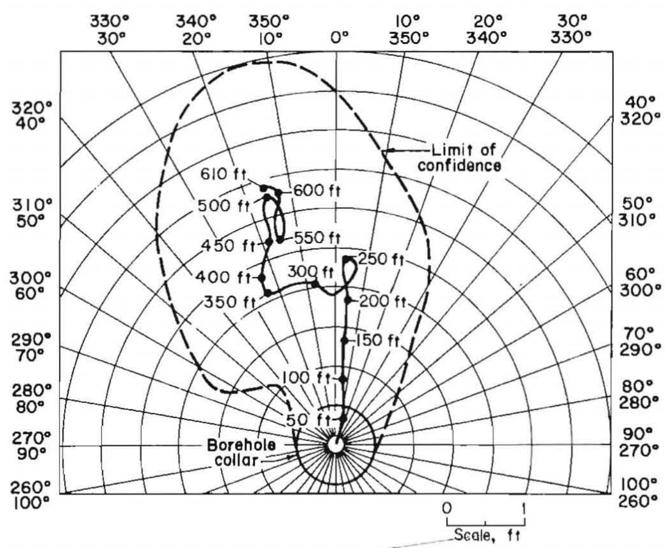

FIGURE 4.—Borehole directional survey of station BH1.

bottom of the borehole was only 3.5 ft, sharp deviations of the borehole, due to the spiraled drill path, prevented placement of a borehole anchor at the desired depth of 615 ft, which is 5 ft above the coalbed.

ROCK MASS CHARACTERIZATION

An assessment of geologic and mechanical rock properties of the entire unit of strata overlying the longwall panel at the mine site was conducted to relate these characteristics to caving height and lateral overburden movement. To accomplish this, geophysical logging was carried out over the entire length of each of the two boreholes.

Figure 5 is a summary of the characteristics obtained for the Pittsburgh and Sewickley interburden at the longwall site. The characteristics include: geologic description, strength index from well logs, uniaxial compressive strength, indirect tensile strength, and rock quality designation (RQD) (4). As the figure shows, the immediate roof rock

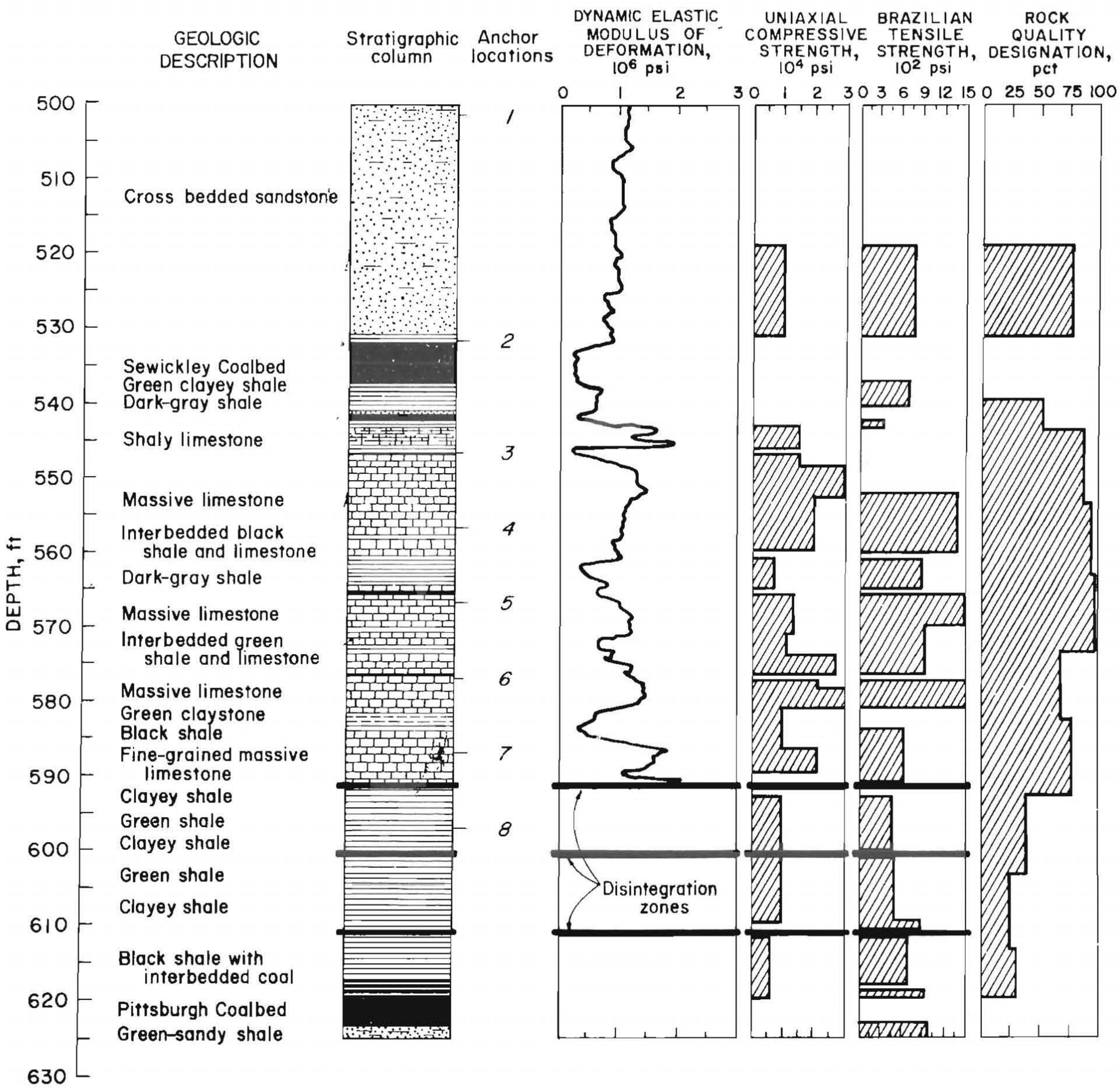

FIGURE 5.—Geologic and rock strength characterization of BH1.

(approximately 28 ft) above the Pittsburgh Coalbed is mainly composed of weak shales with a low RQD. Since the RQD values shown were calculated over each 10-ft core run, the three clayey shale units (indicated as "disintegration zones" in the figure) do not specifically stand out as weak zones. However, each of these units disintegrated upon removal from the core barrel. As will be discussed later, it is probable that caving height was coincident with one of these horizons.

BOREHOLE BH1

American Society for Testing and Materials (ASTM) standards were used for strength evaluations of the NX core from BH1, which included uniaxial compressive strength and Brazilian tensile strength (diametral compression) tests. All the core used was ample in size to meet specimen standards, and a statistically significant number of specimens were tested for most of the rock types recovered. Mechanical property data could not be obtained for several areas in the borehole because either the core disintegrated during recovery or the lengths of the recovered core were inadequate for the preparation of test specimens. These areas are indicated in figure 5.

After the hole was cored, the bottom 100 ft of the hole was reamed to 6 in for geophysical logging and subsequent installation of the borehole instruments. Unfortunately, by the time geophysical logging was conducted, the tools were unable to proceed beyond 16 ft above the coalbed.

A coal suite of geophysical tools was used at the site. These tools included caliper, natural gamma, density, resistivity, spontaneous potential, temperature, fluid conductivity, and sonic. The sonic and density logs were used to calculate a strength index for the area of the rock above the coal seam where the extensometer anchors were positioned.

The following equation was used to give a relative strength value for those sections of the overburden which could not be tested in the laboratory:

$$E_d = \frac{\rho b}{(\delta t)^2} \times 3.36 \times 10^9$$

where ρb = bulk density, g/cm^3,

δt = interval transit time, μs/ft,

and E_d = dynamic elastic modulus of deformation, psi.

This equation was developed by Schlumberger Well Services (5) and relates the sonic and density logs to the dynamic elastic modulus of deformation. The value is not to be regarded as an absolute strength value but rather as an upper limit of the possible strength of the rock. As compared with actual laboratory tests of specimens, the strength index showed a good correlation between low-index values and corresponding low-strength test values. For the higher strength test values, the strength index often indicated a relatively higher strength than did the strength value that resulted from laboratory tests. Bond (5) offers an explanation for this relationship:

> ... a competent appearing formation could be fractured enough to weaken the rock structurally but not enough to create an observed effect on the logs. On the other hand, formations appearing weak on the strength-index curve could not be considered stronger than the calculated index. Therefore, the strength index should be considered an indication of the upper limit of bed competence.

BOREHOLE BH2

Borehole BH2 was drilled from a surface elevation of 1,056.68 ft above mean sea level to an overall depth of 663 ft. Figure 6 shows the geologic description

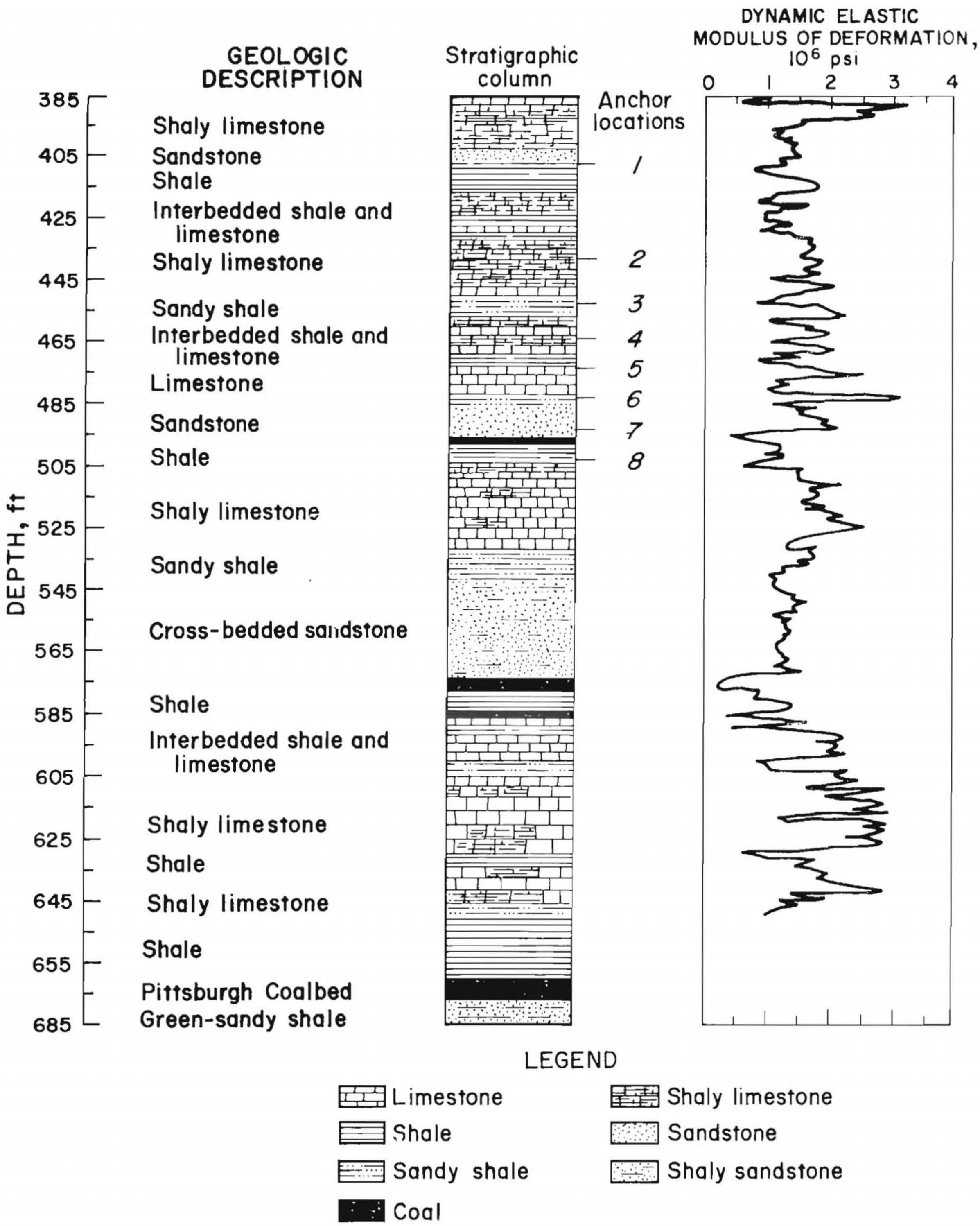

FIGURE 6.—Geologic and rock strength characterization of BH2.

and rock strength index for BH2 as interpreted from the geophysical logs. Unfortunately, as was the case with BH1, the bottom of BH2 was inaccessible; therefore, geophysical logging could be conducted only from a depth of 656 ft to the surface. This 656-ft level corresponds to 7 ft above the top of the Pittsburgh Coalbed. Coring was not deemed necessary as analyses of exploration borehole logs obtained from the mine revealed little lateral variation in geology between the boreholes; therefore, strength values were assumed to be similar.

In addition to physical property testing of the immediate roof rock, in-mine geologic mapping was conducted in the gate roads of the monitored panel. All clastic dikes, slips, and roof falls were recorded, as shown in figure 7. A high frequency of clastic dikes (often referred to as clay veins) is found throughout the study area. These dikes are characterized as infilled, normal,

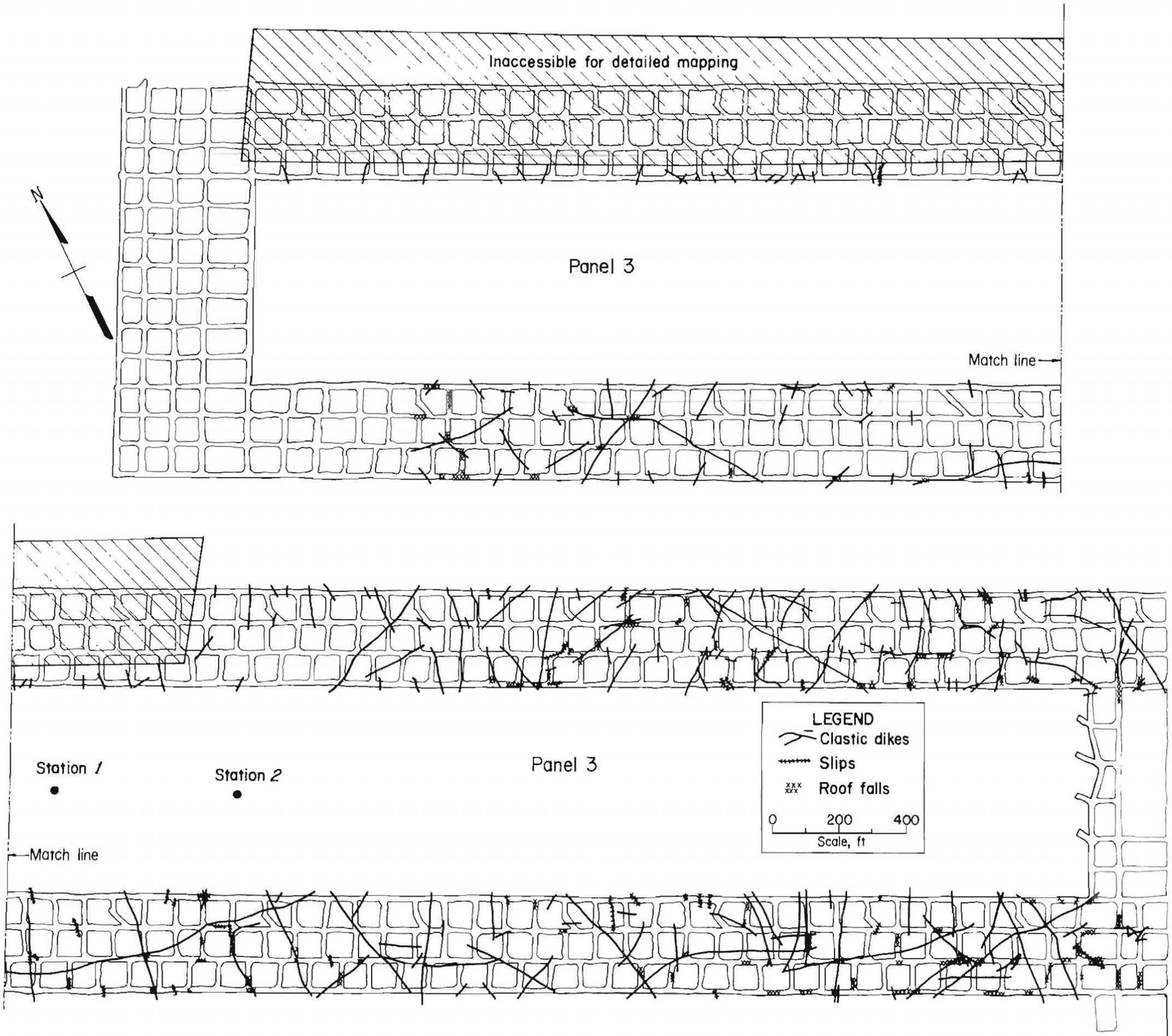

FIGURE 7.—Roof falls and geologic anomalies of gate road entries adjacent to study panel.

fault-type fractures with a clay matrix and inclusions of coal, sandstone, and shale. The dip of the normal fault-type fracture ranges from the vertical to 45°, with as much as 3.3 ft of vertical displacement along the fault plane. At this site, the dikes had no obvious preferred orientation, although their relatively close spacing may have facilitated caving of the gob. Otherwise, observations showed that the dikes only adversely affected ground control in isolated areas.

Coal cleat measurements were also taken at the site. The mean orientations of the butt and face cleat were determined to be N25°E and N65°W, respectively. The direction of mining was subparallel with the face cleat at N60°W. Although no joints were found within the roof rock, other studies have shown that coal cleat orientations often mirror the orientations of joints in overlying strata (4, 6-7). Thus, since the face line of the panel was subparallel with one of the major orientations of the coal cleat, it is possible that jointing in the overburden may have contributed to the caving characteristics of the gob.

Overall, the rock-mass characterization supports the favorable longwall mining conditions that are evident at the mine. The immediate roof is strong enough to remain stable between the tip of the shield line and the face, and weak enough to allow immediate collapse directly behind the shield line. The weak, clayey zones of the immediate roof appear to allow for a consistent caving height and, thus, consistent loading on the shields.

INSTRUMENTATION

Each instrumentation site was comprised of a surface monitoring station and a subsurface instrument installation provided by Roctest, Inc., as shown in figure 8. A premining surface elevation survey was performed at each site to establish an elevation datum, and successive surveys took place at intervals during panel extraction. These surveys allowed differentiation between surface subsidence and subsurface strata activity. Each hole was instrumented with eight-point borehole extensometer and an inclinometer casing, which allowed measurement of vertical and horizontal displacements, respectively. Vertical displacement measurements were made by direct readout of a scale, a continuous recording unit, and a magnetic settlement probe. Lateral displacements were calculated from inclinometer probe measurements.

MONITORING OF VERTICAL STRATA DEFORMATION

To measure vertical displacement of substrata, each borehole was equipped with a multiple-point borehole extensometer. The extensometer is a device that detects vertical strata movement through the use of mechanical spring anchors. The anchors were positioned at specific intervals within the strata and connected to the surface by stainless-steel wires. Depth intervals for anchor placement were selected following an analysis of the recovered core and the geophysical logs. Each anchor was positioned within a distinct stratigraphic member. Interfaces between stratigraphic units were avoided because caving was considered most likely to occur along these planes.

Each of the two 6-in boreholes accommodated eight anchors, the maximum number of anchors that could be used in this borehole diameter. Eight sections of plastic (ABS) inclinometer casing, measuring 1.9 in OD, were prepared at the factory to accept the eight anchors. The remaining sections of inclinometer casing were standard 5-ft sections. The anchor springs were compressed and held closed during installation by nylon strings, which passed through the casing and were attached to opposite pairs of anchor springs (fig. 9).

The anchors were positioned on the casing at the predetermined depths shown in

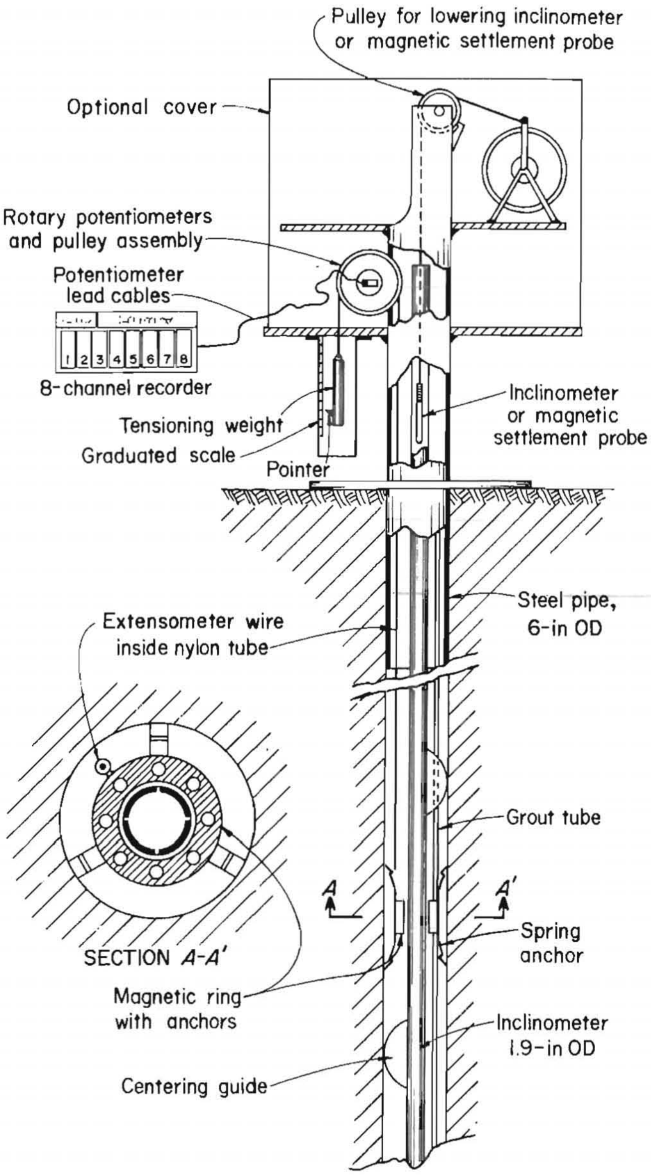

FIGURE 8.—Complete extensometer-inclinometer system. (Courtesy Roctest, Inc., Plattsburgh, NY.)

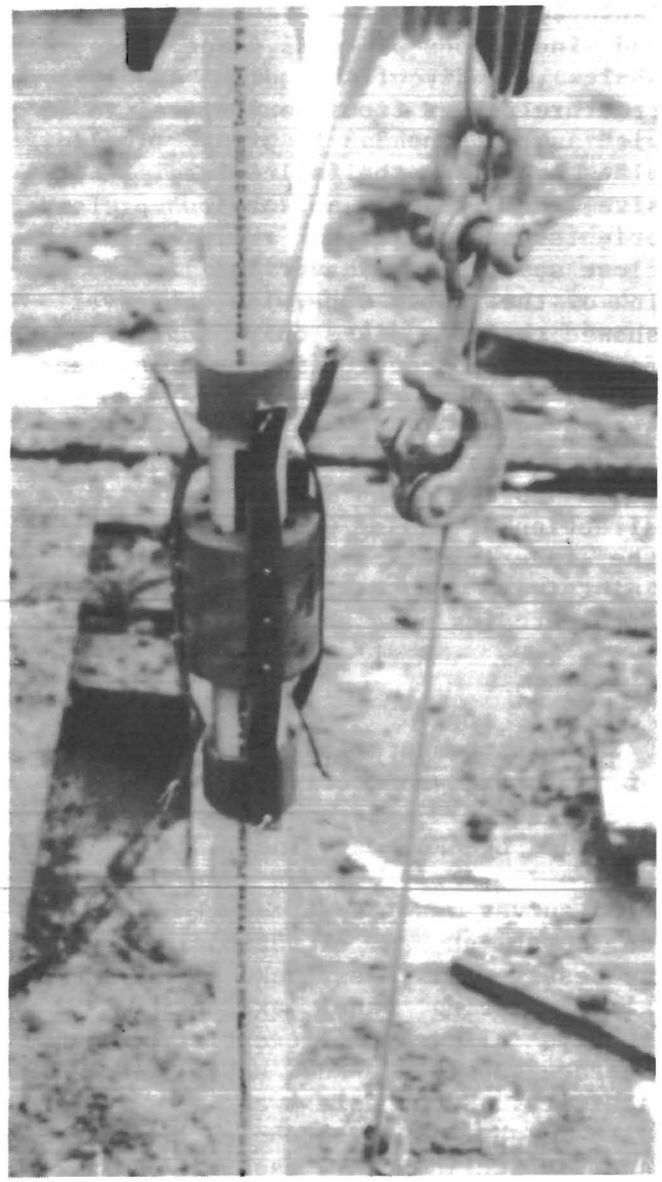

FIGURE 9.—Multiple-point borehole extensometer anchor positioned on inclinometer casing.

figure 5. The 5-ft sections of casing were glued together and lowered down the hole. A grout tube was fastened to the first section of casing and lowered as the system was being assembled (fig. 10). Grouting of the borehole was necessary to seal any water-bearing zones that could have caused water inflow into the mine when the borehole was undermined. The casing remained centered in the hole by means of two sets of ABS centering blades installed on the casing, 5 ft above and below each anchor (fig. 11). A 1/16-in-diam stainless-steel wire surrounded by a 1/4-in-diam oil-filled nylon tubing was attached to each anchor. The tubing was necessary to allow free movement of the wire after the hole was grouted. A wire-tubing assembly was attached to each of the eight anchors and lowered with the anchor and casing assembly. The grout tubing and each of the wire-tubing assemblies were positioned on scaffolding and lowered into the borehole as the 5-ft

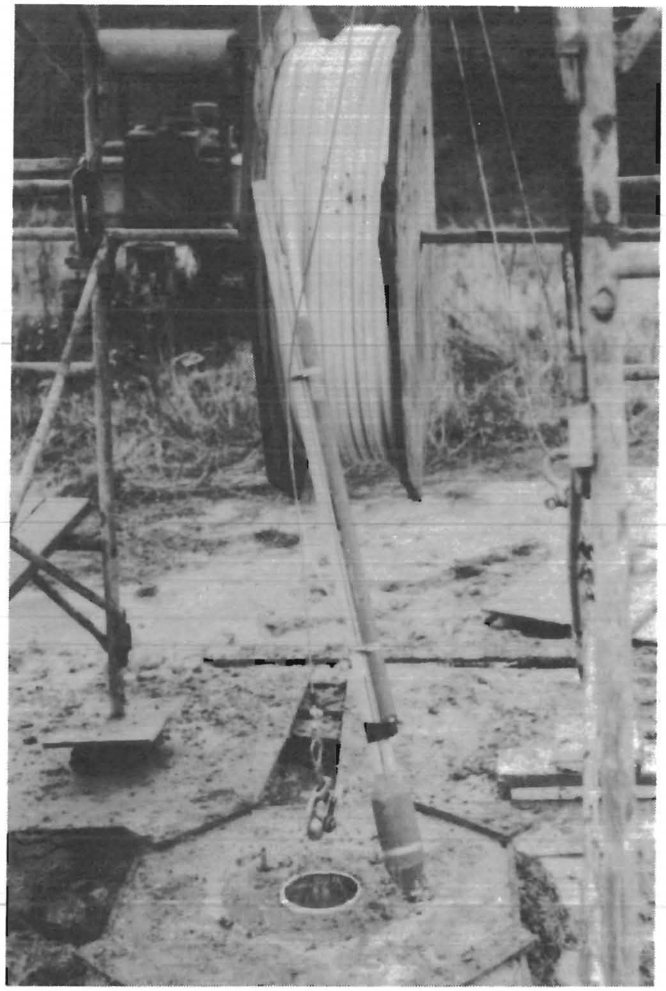

FIGURE 10.—Grout tube attached to lead section of inclinometer casing.

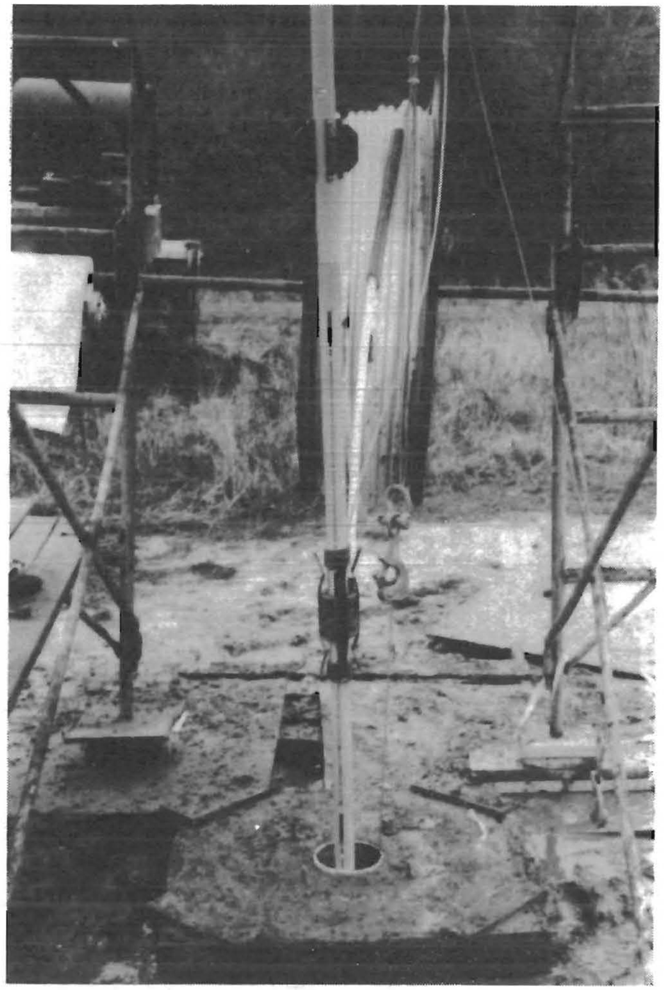

FIGURE 11.—Borehole anchor and ABS centering blades.

sections of casing were added (fig. 12). When the entire assembly had been lowered into the borehole, the anchors were set in place by dropping a weighted knife down through the casing to cut the nylon strings.

A reference head was placed at the top of each borehole. The head consisted of a 6-in-OD steel pipe with a welded circular steel plate used to seat eight potentiometer-pulley assemblies (one for each anchor). Each anchor wire passed through the center of the instrument reference head, over its own pulley, and was fixed with a 50-lb tensioning weight. Graduated scales were fastened to the outside circumference of the head to allow direct readout of displacements. For remote readout, the potentiometer leads were soldered onto a terminal panel to which a continuous recorder was connected. The head also incorporated a large pulley for lowering the inclinometer and magnetic settlement probe.

The magnetic settlement probe, which works by magnetic inductance, was used to verify anchor locations in the strata (fig. 13). Magnetic rings were incorporated into each of the eight borehole anchors, creating a magnetic field inside the inclinometer casing. A reed-switch probe was connected to a graduated cable mounted on a cable reel. An audible buzzer, housed inside the cable

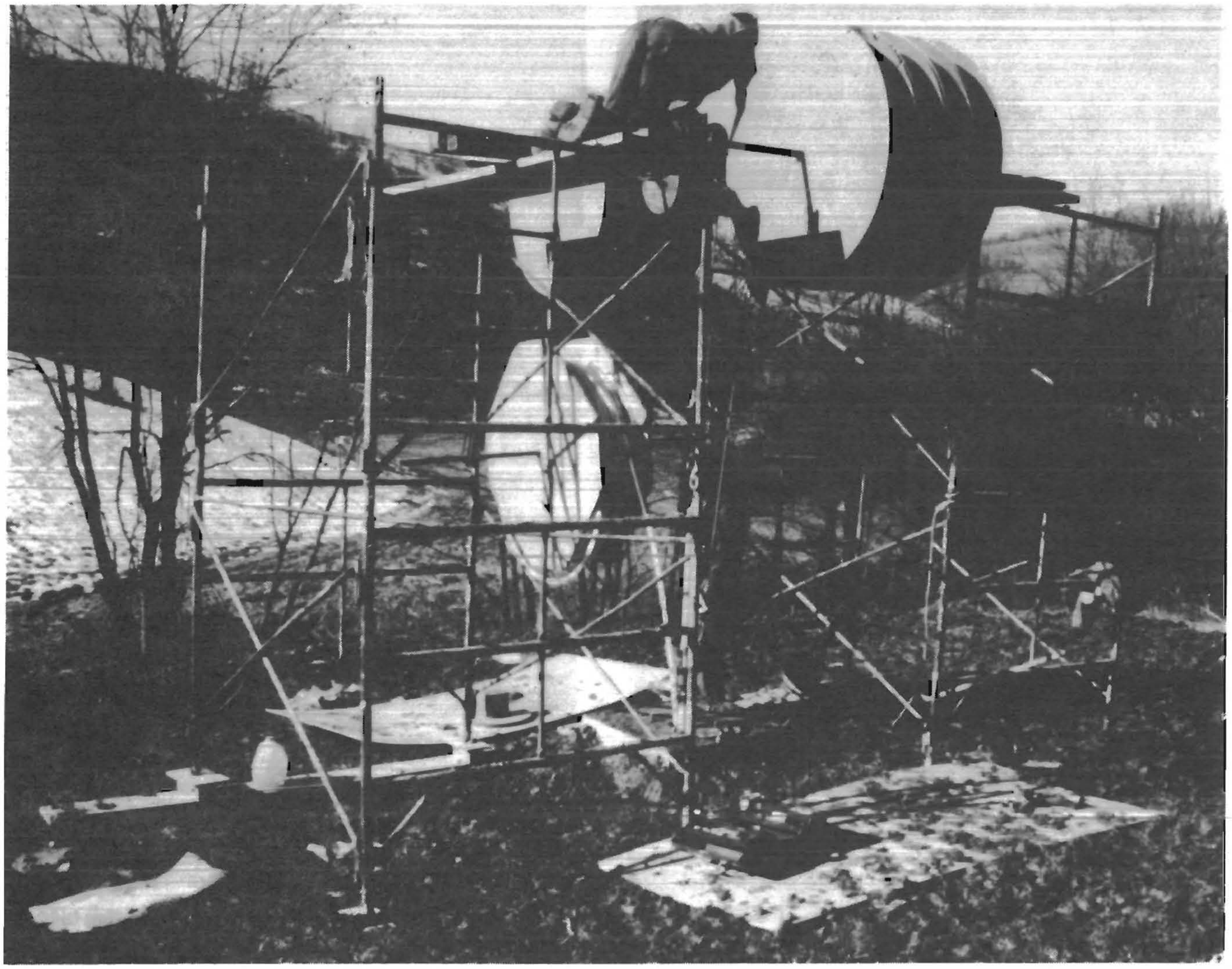

FIGURE 12.—Instrument installation apparatus with mounted grout tube and extensometer anchor wire-tubing assemblies.

reel, was activated by entry of the probe into the localized magnetic field produced by the anchor. This device provided excellent results for verification of anchor locations. However, after mining progressed beneath the borehole, high concentrations of methane began propagating up the borehole, preventing further use of the nonpermissible magnetic probe and the continuous recording unit.

MONITORING OF HORIZONTAL STRATA DEFORMATION

An inclinometer probe was used to measure the progressive changes in the angle of inclination of the casing. These measurements provided an evaluation of lateral movement as mining approached the station. The probe was supported laterally in the casing by guide wheels and suspended vertically by a cable connected to a reel and readout unit. The guide wheels traversed opposing longitudinal grooves spaced equally 90° around the inside circumference of the casing for directional control. Two servo-accelerometers, mounted with sensitive axes 90° apart, simultaneously monitored inclination both parallel and perpendicular to the direction of mining. Recording of data was accomplished by the use of a digital indicator equipped with a magnetic tape cassette recorder. Although the inclinometer probe output is recorded in terms of the angle of inclination, lateral deflections can be calculated easily from these data. Figure 8 illustrates the complete instrumentation system.

FIELD DATA ANALYSIS

Subsidence studies at the mine site indicate that the area of influence of vertical deformation ahead of the longwall face from previously mined panels was approximately 200 ft. Therefore, initial conditions of stations 1 and 2 were established at 700 and 900 ft in advance of the face, respectively, to ensure that mining-induced effects had not yet begun. Surface elevation data were also established for each hole prior to mining to differentiate between surface and subsurface activity. Instrument readings were taken weekly while the face was greater than 200 ft from the station and daily when the face was within 200 ft of each station. Face advance was obtained from the mine daily and surface elevation surveys continued to be made periodically after mining passed beneath the stations.

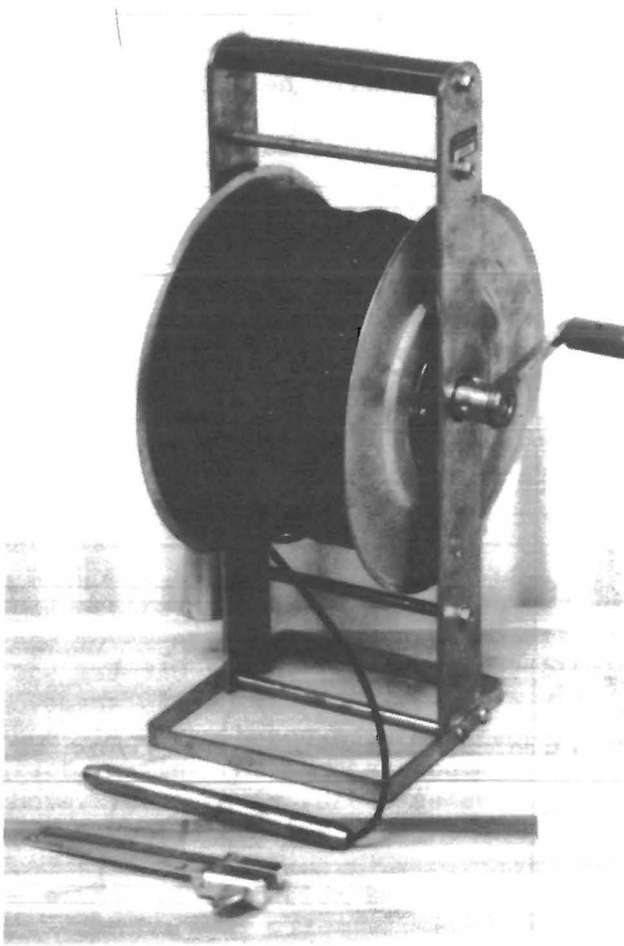

FIGURE 13.—Magnetic settlement probe.

EXTENSOMETER DATA ANALYSIS

To establish the progress of caving, BH1 extensometer anchors were positioned in the mine roof strata as shown in figure 5. Ideally, the deepest anchor in BH1 was to be positioned 5 ft above the height of the extraction. However, since the bottom of the borehole was inaccessible prior to instrument installation, the deepest anchor was set at a depth 23.5 ft above the coalbed.

Anchors in BH2 were positioned as shown in figure 6. These anchors were positioned at greater vertical distances from the coalbed to monitor the fracture propagation nearer the surface.

It is important to note that the anchor displacements shown are with reference to the extensometer head located at the surface. The movements of the extensometer head were determined by surface elevation surveys. The displacements shown in the following figures have not been corrected to include the measured movements of the surface.

Station BH1

Initial anchor movement was detected in all anchors when the face had approached to within 500 ft of station BH1 (fig. 14). Since it cannot be associated with caving, this movement has been attributed to lateral displacements of strata and by a rising surface elevation in advance of the face (fig. 15). As the face drew near and passed beneath the station, anchor positions were recorded hourly based on the assumption that large movements would be seen immediately after the longwall supports passed beneath the borehole. However, anchor movement was not detected at that time. Figure 14 shows that significant movement (caving related) in anchors 2 to 8 began when the face was 35 ft past the station. Anchor 1 (the furthest from the extraction) began moving when the face was 75 ft past the station, the same time surface subsidence began (fig. 15). The abrupt failure of the immediate roof associated with the advance of the longwall supports was not detected by anchor 8, which was positioned 23.5 ft above the extraction. This indicates that 23.5 ft is above the upper limit of the first strata separation. Descriptive geologic logging of the immediate strata revealed three very weak bands (approximately 6 in thick) of soft clayey shale in the immediate 25 ft of roof. These weak zones occurred at heights of 8, 17, and 25 ft, and it is assumed that immediate caving behind the supports occurred up to one of these zones. Using these zones as possible caving horizons and relating each to the following equation yields three different bulking factors for the extraction height of 5.8 ft:

$$H = c + h$$

$$H = ck$$

where h = extracted height, ft,

c = height of caved material from roof level of extracted height, ft,

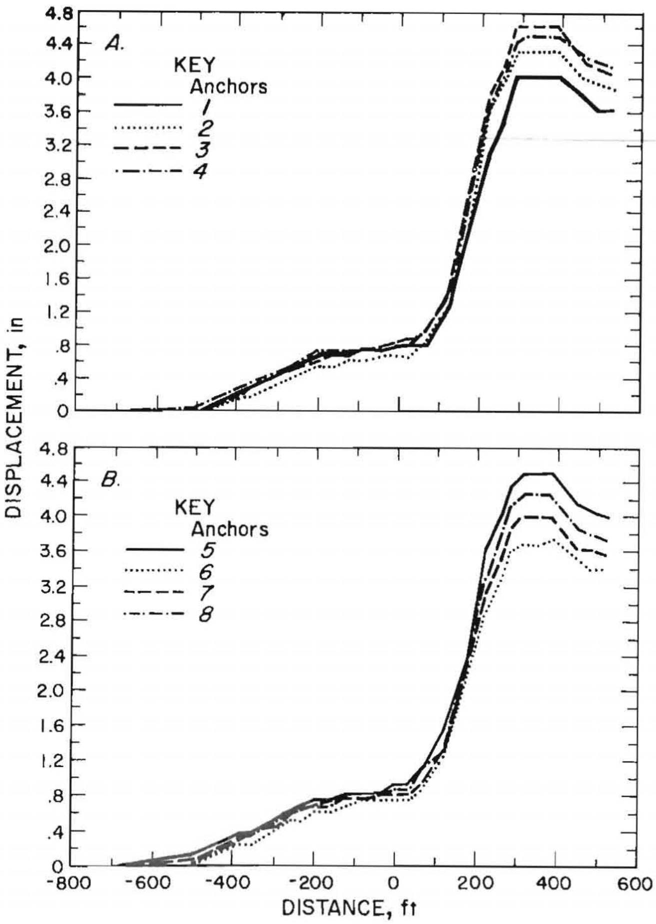

FIGURE 14.—Station BH1 extensometer displacements for anchors 1 to 8.

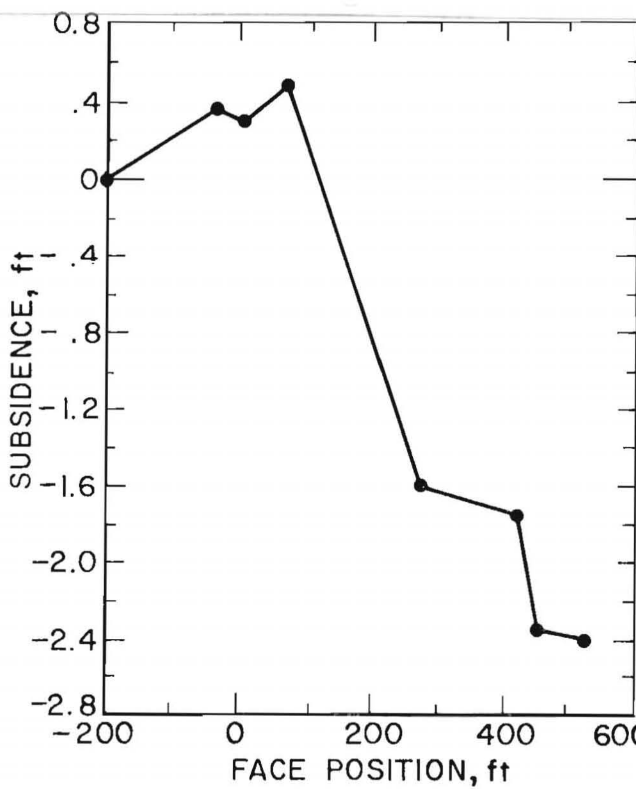

FIGURE 15.—Surface elevation survey data for station BH1.

H = distance from floor level to caving horizon, ft,

and k = bulking factor, unitless.

Substitution yields:

$$k = \frac{h}{c} + 1$$

The caving horizons of 8, 17, and 25 ft yield bulking factors of 1.72, 1.34, and 1.23, respectively. The fact that anchor 8 did not begin to detect small movements until the face had passed 35 ft beyond station 1 suggests that immediate caving behind the supports occurred at some height less than 23.5 ft. The bulking factor of 1.34 for the 17-ft horizon closely corresponds to the commonly used value of 1.33 for bulking of shale, which comprises 30 ft of the immediate roof. Therefore, caving is assumed to have occurred up to the 17-ft horizon. Surface subsidence and anchor movement occurred concurrently when the face was between 75 and 290 ft past the borehole (figs. 14-15). Maximum surface subsidence during this period was 2 ft, and maximum extensometer movement of anchor 8 was 4.25 in. The fact that both surface and small subsurface movements occur at the same time and at a distance of 75 ft beyond station 1 suggests that the entire overburden member above the assumed caved height of 17 ft began to sag and compact the gob material.

Although the greatest amount of subsidence occurred between 75 and 290 ft, surface movement did not cease until the face was 530 ft past the station. Anchor movement ceased at 290 ft. This difference is attributed to the closure of fractures in the strata above the anchors. Closure is seen as an apparent upward movement of anchors.

Station BH2

The behavior of the anchors in station 2 was slightly different than that of station 1. This difference may be attributed to the unpredictable nature of surface movements ahead of the face. For instance, at 146 ft in advance of the face, an apparent upward movement of the anchors occurred (fig. 16). Figure 17 shows that a surface swelling ahead of the face occurred at 367 ft. As the face moved from 367 ft to within 120 ft of the station, a decrease in surface elevation occurred. This decrease in elevation appeared as negative readings at the reference head and, therefore, it appeared that the anchors had moved up. Figure 15 shows that different surface subsidence behavior occurred ahead of the face at station 1, resulting in correspondingly different apparent anchor displacements.

Movement of the anchors began 100 ft after the face passed beneath station 2. As previously stated, significant movement of anchors 1 to 4 (the uppermost anchors) in station 1 began when the face had progressed a distance of 75 ft past

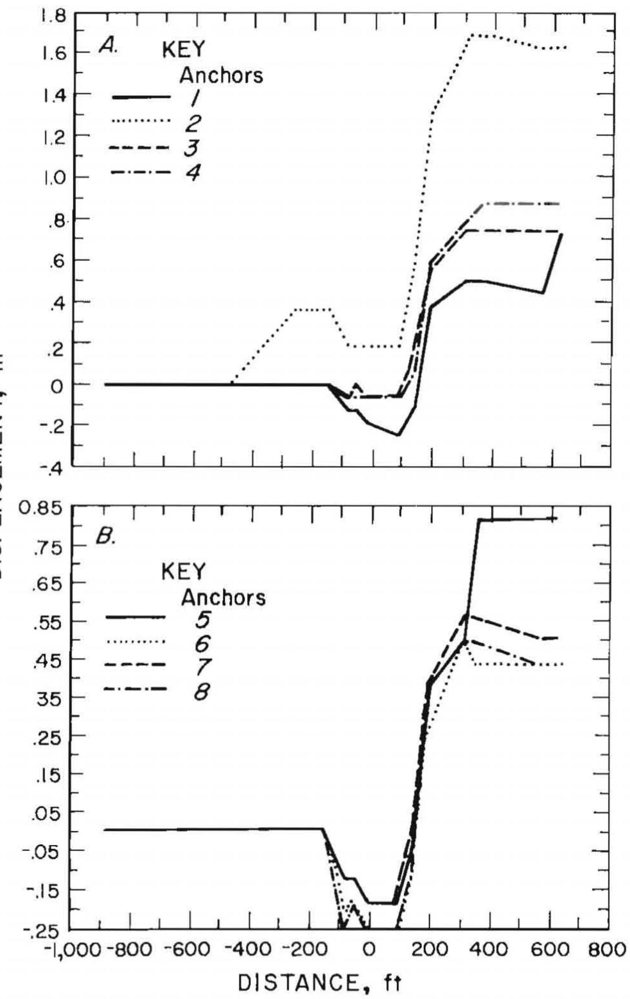

FIGURE 16.—Station BH2 extensometer displacements for anchors 1 to 8.

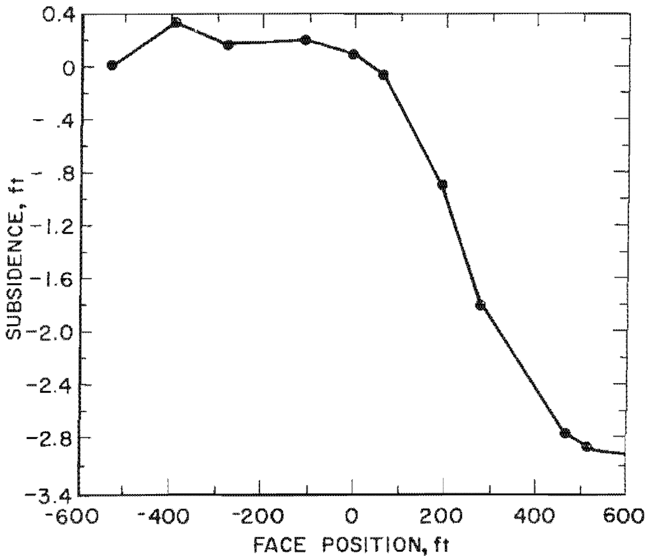

FIGURE 17.—Surface elevation survey data for station BH2.

the station. Thus, the initial movement at station 2 occurred when the face was 25 ft further past the station than when the first occurrence of anchors 1 to 4 of station 1 began to move. This indicates a propagation of fractures further above the coalbed as the face draws further away from the station. The maximum displacement of the deepest anchor was less than the maximum of the uppermost anchor in station BH1. This could be expected since the deepest anchor in station BH2 was positioned further above the coalbed than the highest anchor in station BH1. As with station BH1, surface and subsurface movement occurred concurrently, indicating a gradual movement of the rock mass onto the consolidating gob.

INCLINOMETER SURVEY DATA ANALYSIS

The inclinometer was used to detect lateral deflections in advance of the longwall face. The inclinometer probe measured the angle of tilt of the casing within the borehole in two directions, parallel and perpendicular to the centerline of the panel. The following analysis will refer to an A and B direction. The A direction is parallel to the direction of mining. Positive A deflections are movements toward the direction of mining and negative deflections are in the opposite direction. The B direction refers to deflections perpendicular to the direction of mining. Positive deflections are movements toward the previously mined panel and negative deflections show movement toward the adjacent unmined panel.

Station BH1

The inclinometer casing in BH1 was installed to a depth of 604 ft, which was 16 ft above the mined height of the Pittsburgh Coalbed. Initial readings were established 290 ft in advance of the approaching longwall face. Although the inclinometer casing was lowered to a depth of 604 ft, the initial readings could only be taken to a depth of 489 ft. This blockage was attributed to the sharp deviation in direction of the borehole at a depth of 500 ft as shown on the directional survey, which was performed immediately after the hole was drilled (fig. 4).

Readings were taken daily as the face approached and passed beneath the monitoring station, but had to be discontinued after the face had passed 5 ft beneath it since high concentrations of methane were being vented up the inclinometer casing. Inclinometer survey data show that the vertical strata movements discussed in the previous section were accompanied by lateral deflections of the strata. Figure 18 shows the variation of lateral deflection at station BH1 relative to face advance. Figure 18*A* shows movement in the A direction (parallel to the direction of face advance), and figure 18*B* shows movement in the B direction (perpendicular to the direction of face advance).

Figure 18 reveals that small shear zones begin forming at various depths in the borehole 263 ft in advance of the face. Larger deviations from the initial reading began to occur when the face was 157 ft from the borehole. In both the A and B direction, movement began to develop at a depth of 112 ft. Geophysical logs show a soft, fire clay at this depth. Two other areas of activity at this face position occur at depths of 325

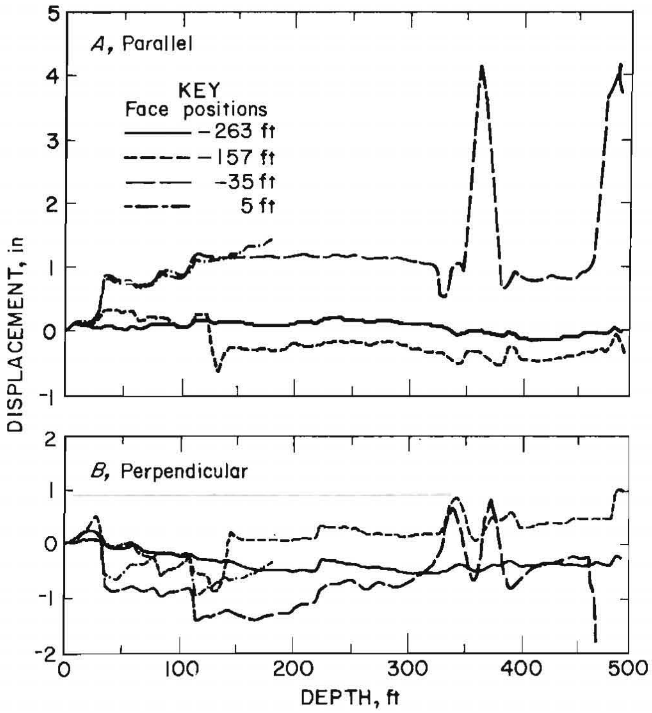

FIGURE 18.—Lateral displacements of BH1 parallel (*A*) and perpendicular (*B*) to the direction of face advance.

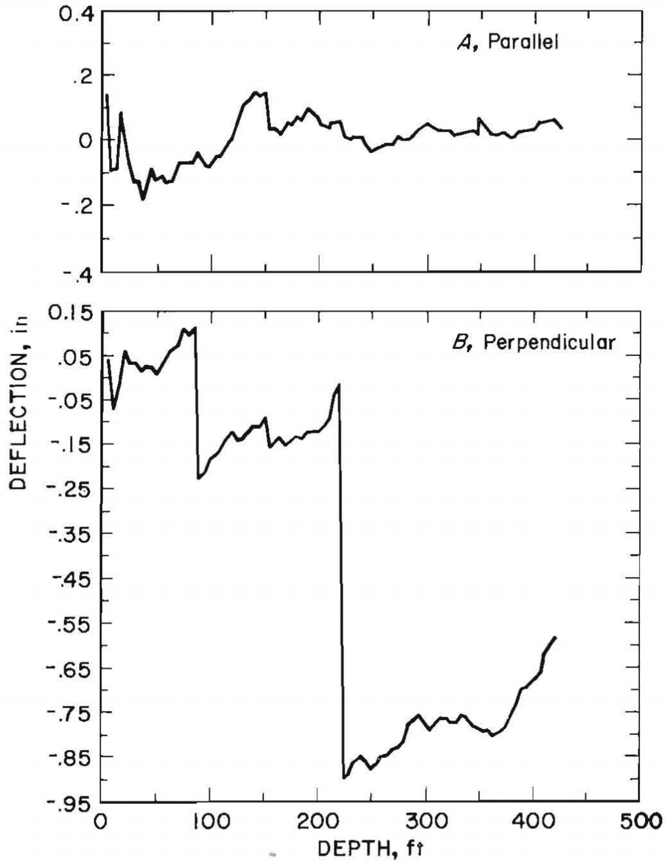

FIGURE 19.—Lateral displacements of BH2 parallel (*A*) and perpendicular (*B*) to the direction of face advance.

and 370 ft, where the strata again are composed of fireclay.

When the face advanced to within 35 ft of the borehole, greater movements were apparent. Three distinct areas are discernible. The aforementioned depths of 112, 325, and 370 ft show relatively large displacements (fig. 18). Maximum deflections of 4.2 in can be seen at 360 and 480 ft. A shear zone begins to form at 460 ft in a 5-ft layer of carbonaceous shale that is situated between an upper member of sandstone and a lower member of limestone. Quantification of the relative strength of these members using the strength index equation previously discussed, indicates that sandstone and limestone are seven times stronger than the carbonaceous shale. When the face passed beneath the station and was at a distance 5 ft beyond the borehole, a shear zone developed at a depth of 179 ft, prohibiting the probe from progressing past this point. A final reading (not shown in figure 18) taken after face advance had progressed over 195 ft past the station revealed that the highest progression of shear had extended to within 46 ft of the surface.

Station BH2

Due to a mechanical malfunction of the probe and cable lowering system, only one inclinometer survey in addition to the initialization survey, was recorded at station 2. Figure 19 shows the lateral disturbances that occurred at 79 ft in advance of the face. Although no major deflections (>0.2 in) were observed in the A direction, the B direction shows a disturbance (0.9 in) at 225 ft. The geophysical log of this borehole shows that a 2-ft fire-clay member lies at this depth. This finding is consistent with the observations at station 1.

RESULTS

Significant anchor movement and surface subsidence was detected when the face had progressed 35 ft past station 1. Surface and subsurface movements continued to increase until the face had advanced to 290 ft past the station. At this point, positive anchor deflection ceased. Surface subsidence continued slightly to a face position of 430 ft. Differential surface and subsurface displacement is attributed to the closing of fractures in the strata above the anchor positions. This appeared on the reference head as upward anchor movement.

Anchor 8 (the deepest) in station 1 did not detect an abrupt failure of the roof immediately after passage of the supports beneath the borehole, but moved a total of 4.25 in as the face moved 310 ft past the station. This indicates that caving of the immediate roof occurred at a height less than 23.5 ft above the top of the mined height. Thus, the actual bulking factor must be greater than 1.25.

Three very weak bands of clayey shale are present between the top of the mined height and anchor 8. It is assumed that immediate caving occurred at one of these weak horizons. Calculation of a bulking factor based on caving to the 17 ft horizon yields an estimated bulking factor of 1.34.

Inclinometer surveys show the formation of a number of shear zones throughout the length of the borehole. Shear zones were detected in station 1 at a distance of 263 ft in advance of the face. As the face drew nearer to the station, lateral displacements in the borehole became more apparent. A comparison of inclinometer survey data and geophysical logs revealed that shear zones are associated with weak-strata horizons. These weak horizons occurred in fire-clay material at depths of 46, 112, 325, and 370 ft. Another displacement at 480 ft occurred in a 5-ft layer of carbonaceous shale. As the face progressed beneath the borehole, a shear zone developed at a depth of 179 ft and prevented further inclinometer readings. The final shear zone detected was at a depth of 46 ft.

The single inclinometer survey taken at station 2 reaffirms the events that occur in station 1. Thus, it can be seen that the shear zones detected by the inclinometer appear to correlate with the weak-strata members overlying the coalbed.

CONCLUSIONS

The primary goal of this investigation was to define the height of caving immediately behind the advancing longwall supports. Previous estimates of caving height, according to Wilson (1) and Wade (2), predict the height of caving to be 2 and 4 times the extraction height, respectively. This investigation revealed that caving occurred at a height less than 23.5 ft above the coalbed and in fact most likely occurred at a height coincident with one of three clayey shale zones. These zones are located at 8, 17, or 25 ft above the coalbed and calculation of bulking factors based on caving to each of these horizons yields values of 1.72, 1.34, and 1.23, respectively. The fact that 1.34 closely corresponds to the commonly used bulking factor for shale (1.33) suggests that the caving horizon occurred at 17 ft or 3 times the extraction height.

Inclinometer data revealed another characteristic of longwall strata behavior. Comparison of inclinometer data with geophysical logs showed that the major lateral deflections occurred in weak strata (i.e., fire clay and carbonaceous shale).

Based on these observations, the behavior of strata over longwall panels appears to be largely dependent upon lithology. Future studies should allow the caving behavior of various lithologies to be characterized.

RECOMMENDATIONS

From the experience gained during the present study, several modifications to instruments and procedures can be recommended. For example, the drilling of a straight borehole to the top of the coal seam is essential. Extensometer anchors should be set within the first 5 ft of the top of the extraction to ensure detection of immediate movement after the supports pass. The hole should be larger in diameter (the present study utilized a 6-in-diam borehole) and the area of the borehole where the anchors are located should not be grouted since in a fully grouted hole, small lateral displacements may tend to inhibit the movement of the extensometer wires. The authors believe these changes would result in better data regarding the caving height of immediate roof behind longwall supports.

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INT.-BU.OF MINES,PGH.,PA. 28337